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THEORETICAL INVESTIGATION OF CURRENT INSTABILITIES AND TERAHERTZ OSCILLATIONS IN A TWO-DIMENSIONAL ELECTRON FLUID

Final Technical Report

by

M.I. DYAKONOV

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United States Army

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SUMMARY

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Keawords: terahertz radiation, infrared radiation, plasma waves, shallow water, instability, two dimensional electron fluid, Field Effect Transistor.

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1. STATEMENT OF THE PROBLEM

The purpose of this work is to study theoretically the consequences of the recently discovered instability of a current-carrying state in a two dimensional electron fluid in a Field Effect Transistor (FET). It was shown by M.I.Dyakonov and M.S.Shur [1] that at normal concentrations and not very low temperatures the motion of the electron fluid in the FET channel is described by hydrodynamic equations which coincide with those for shallow water [2], and that the steady state with a dc current is unstable against plasma wave generation. In submicron gate FETs the plasma oscillation frequency is in the terahertz frequency range. This spectral range has a significant potential in complementing the microwave and infrared bands for remote sensing, atmospheric profiling, surveillance etc.

A number of problems arises: What is the nonlinear regime of plasma oscillations which should built up as a result of this instability? What influence have the boundary conditions at the source and drain contacts on the instability threshold? What is the role of the viscosity of the electron fluid? What other hydrodynamic phenomena, similar to those known in shallow water, may occur in the electron fluid?

These are the problems that we addressed in this work. In addition, we studied the consequences of the negative differential electron mobility in GaAs-based FETs (an analog of the Gunn effect in three dimensional devices), and we proposed a novel device - the "electronic flute" - in which plasma waves are excited by dc current in the same way as sound waves are excited by air jets in wind musical instruments.

2. BACKGROUND

Plasma waves in a FET channel were predicted theoretically [3,4] and observed experimentally in Silicon Metal-Oxide-Semiconductor inversion layers by absorption of far infra-red radiation [5]. Some very weak emission at the plasma frequency was also observed [6] due to the Smith-Purcell effect in Silicon with modulated gate. It was recently shown [1,7] that in short FETs where electrons experience practically no collisions with impurities and/or phonons during the transit time, but where high electron concentration results in many electron-electron collisions, the two dimensional (2D) electrons exhibit interesting hydrodynamic behaviour. Such is the case for high-mobility devices with 2D electron concentration 10^{12} cm^{-2} at nitrogen or even room temperature, when the Fermi energy, the Bohr energy and the thermal energy kT are roughly equal.

Under such conditions the electrons are described by hydrodynamic equations which are exactly the same as those for shallow water [2], the water level corresponding to the gate-to-channel voltage. The shallow water waves correspond to the plasma waves in the FET channel. These waves have a linear dispersion law with a velocity s given by the formula

$$s = (eU/m)^{1/2} ,$$

where e is the electron charge, m is the electron effective mass, and U is the gate-to-channel voltage swing. The value of s is typicaly on the order of 10^8 cm/s. Thus, for submicron gate length, L , the plasma oscillation frequency which, for the fundamantal mode is on the order of s/L , lies in the terahertz frequency range. This frequency can be easily tuned by changing the gate voltage U.

It was also shown in Refs. 1,7, that for the boundary conditions of a short-circuited (at high frequency) gate-source, and open gate-drain, the steady state of a current-carrying FET is unstable against spontaneous generation of plasma waves. This instability is due to the plasma wave amplification during reflection at the drain side of the channel (the reflection coefficient is greater than unity, because of the difference in velocities for waves travelling in opposite directions; the velocities are $s+v_0$ and $s-v_0$, where v_0 is the drift electron velocity).

Because of the shallow water analogy, various new hydrodynamic phenomena should take place in the electron fluid in a FET, such as the "choking" effect, shock waves and soliton propagation. This opens a new field of studies of the two dimensional electron fluid properties.

3. THEORETICAL APPROACH

The theoretical approach utilized in this work is based on the hydrodyanamic equations derived in Refs. 1,7. These include the Euler equation of motion for the electrons, the continuity equation, and the linear relation between the surface electron concentration in the channel and the gate-to-channel voltage swing. We assume that this relation is valid locally even in the case when the voltage swing varies in space (the "graduate channel approximation"), which is true if the spatial scale of the voltage variation is large compared to the gate-channel separation.

The viscosity of the electron fluid (just like in normal fluids) can not be calculated exactly for the case of strongly interacting electrons, which is if interest to us. It may be, however, easily estimated, assuming that the mean free path for electron-electron collisions is on the order of the interelectronic distance, as explained in Section 2. We find that the viscosity is relatively small, however in some cases it should be taken into account.

Effects of heating of the electron fluid are neglected in this work, which is justifiable at low enough fields and low current values.

In studying the weakly nonlinear oscillations above, but close to the instability threshold, we use the conventional mathematical methods, developed for solving similar problems in hydrodynamics and laser physics.

In all of our studies we restrict ourselves to one dimensional problems, i.e. we assume that the electron concentration and drift velocity depend on one coordinate only, and that everything is uniform in the other direction.

4. NONLINEAR REGIME OF PLASMA OSCILLATIONS ABOVE THE INSTABILITY THRESHOLD

An analytical theory of the nonlinear evolution of the current instability in a FET was developed, in which both the internal friction, caused by the electron viscosity, and the external friction, due to collisions with impurities and/or phonons, were taken into account [8].

Assuming the total friction to be small, i.e. the quality factor of the plasma wave resonator, formed by the channel and the source and drain contacts, to be high enough, we find the threshold current, at which the instability occurs. Since the role of viscosity increases with increasing wavenumber, the threshold current is greater for higher modes. Above, but close to the threshold for the fundamental mode, its amplitude should grow in time, while the other modes should decay, being below the threshold. The mechanism, by which stationary oscillations are built up, is the following. The fundamental mode is pumped by the dc electron flow. Due to the nonlinearity, the energy is transfered from the fundamental mode to the higher modes, which decay due to viscosity. Thus a stationary state will be achieved, in which the mean energy of oscillations is constant. Not far from the threshold for the fundamental mode, the nonlinear terms are small. This allows to find analytically the stationary amplitude of the fundamental mode of plasma oscillations. It was found that this amplitude is proportional to the square root of the difference between the actual current and its threshold value.

For higher currents the exponent in the current dependence of the amplitude was found to change from 1/2 to 1/4. For currents strongly exceeding the threshold value no analytical results were found. We

anticipate that in this case the instability should lead to formation of shock waves with step-like distribution of electron concentration and drift velocity. We suppose to study this regime later on by numerical computer simulation.

The onset of plasma oscillations at the instability threshold should change the dc current-voltage dependence of the device. Our theory predicts that the differential resistance should have a sharp step at the instability threshold. The reason for this is that an additional mechanism of energy dissipation, caused by electron viscosity, becomes active above the oscillation threshold.

5. NEW MECHANISM OF CURRENT SATURATION IN A FET: THE "CHOKING" EFFECT

The hydrodynamic properties of the two dimensional electrons in a FET may lead to a new mechanism of the drain current saturation , different from the two conventionbal mechanisms - the channel pinch-off and the drift velocity saturation. This new mechanism is related to the effect of *choking* of the electron flow, similar to the choking of the shallow water flow, or the choking of the gas flow in a pipe. The choking of the gas flow occurs when its velocity approaches the sound velocity at the downstream edge of the pipe. When this condition is reached, the flux saturates: it cannot be increased further by a decrease of the pressure at the downstream end of the pipe. Analogously, the choking of the electron flow should take place when the electron velocity reaches the plasma wave velocity at the drain side of the channel [9].

We studied this phenomenon theoretically in Ref. 9, using the previously derived hydrodynamic equations [1] and taking into account the electron momentum relaxation due to collisions with impurities and phonons. We have shown that the choking effect does, indeed, lead to current saturation in a FET. However for this new mechanism to be more efficient than the channel pinch-off mechanism [10] the condition

$$L << s\tau$$

should be fullfilled, where L is the gate length, s is the plasma wave velocity, and τ is the momentum relaxation time. This inequality specifies the condition under which the current-voltage characteristic is strongly affected by choking. One can see that it may be fullfilled for short enough gate lengths. Another competing mechanism is the drift velocity saturation at $v = v_{sat}$. Obviously, the choking effect would be more important if $s << v_{sat}$.

We have shown that the choking effect may be the main mechanism of current saturation at relatively low electron concentrations and low temperatures, e.g. in GaAs-based FETs this would be the case at $T = 10$ K for electron concentration $3 \cdot 10^{10}$ cm^{-2}, and submicron gate lengths.

6. ROLE OF THE BOUNDARY CONDITIONS FOR THE INSTABILITY THRESHOLD

The increment for the growth of the amplitude of the plasma waves was derived in Ref. 1 for the simplest case of ideal boundary conditions, when the gate-to-channel voltage is fixed at the source contact, and the current is fixed at the drain contact. This means that at high frequencies the source-gate impedance is zero, while the drain-gate impedance is infinitely large. Such ideal conditions do not exist for real devices, thus it is of interest to analyse the general case of arbitrary boundary conditions or, in other words, arbitrary gate-source and gate-drain impedances.

The problem was solved by considering the linearized hydrodynamic conditions with boundary conditions, reflecting linear relation between current and voltage with given impedances at source and

drain. For the case of purely reactive (imaginary) impedances it was found that the current instability always exists, so long as the absolute value of the drain impedance is greater than that of the source. In this case the product of the source and drain plasma wave reflection coefficients is greater than unity, which insures the growth of the amplitude of plasma oscillations. However the threshold current increases with decreasing difference of the source and drain impedances.

The relevant parameter is the ratio of the boundary impedance to the device impedance (which is defined by the device gate-to-channel capacitance). Thus, in order to have the threshold current as low as possible, it is essential to have the capacitance loaded at the source much greater than the device capacitance, and to have the parasitic capacitance at the drain much smaller than the device capacitance.

For the case of active (real) impedances additional damping of the plasma waves occurs, due to energy dissipation during reflection. Accordingly, this leads to the decrease of the plasma oscillation increment and to the increase of the threshold current. Eventually, for high enough gate-to-source resistance, the dc current-carrying state becomes stable.

7. INSTABILITY DUE TO NEGATIVE DIFFERENTIAL MOBILITY

An essential transport property of some semiconductor compounds, such as GaAs or InP is the negative differential mobility (NDM) in high electric fields. This property leads to the Gunn effect in bulk devices. GaAs-based FETs often show experimentally negative differential resistance and instability at high source-drain voltages. However, there was no analytical theory describing the consequences of NDM in the two-dimensional FET channel. Such a theory was recently developed [11] within the frame of our project. The problem is very much different from the three dimensional case because of the difference in the relation between charge and electric field in a gated conducting layer and in the bulk. We study steady state field distributions in the channel and their stability using the local field model and the gradual channel approximation.

We have shown that in a FET with a short enough channel two steady states may exist at certain values of the drain current. The steady state corresponding to higher voltage should exhibit a negative differential resistance and may show convective or absolute instability. The growth in time of small fluctuations was found to be governed by the diffusion law with a *negative* diffusion coefficient, in contrast to the low field case, where, as we have shown previously [12], charge relaxation in a FET obeys the diffusion law with a positive diffusion coefficient.

This instability, just like the hydrodynamical one, may lead to plasma wave generation. It should be stressed that the nature of instabilities related to NDM, which may occur at high enough source-drain voltages is quite different from, but complementary to, the plasma wave instability considered in Refs. 1,7.

8. TWO DIMENSIONAL ELECTRONIC FLUTE

In our paper [13] we have discussed FET-based devices which are more complex than a ballistic submicron FET considered in Refs. 1, 7 and which are analogous to wind musical instruments where sound is excited by air jets. We have shown that the behaviour pf plasma waves in gated two dimensional systems is governed by the same equation as for sound waves. Therefore, resonant structures, similar to those in musical instruments, may be realized for the plasma waves, and these waves can be excited by direct current just like wind musical instruments are excited by air jets. However, the plasma wave velocity is much greater than the sound velocity and the FETs are very small. As a consequence, the plasma frequencies are in the terahertz range. These plasma waves are accompanied by a variation of the dipole moment created by charges in the FET channel and mirror

image charges in the gate and, hence, should cause the emission of far infrared electromagnetic radiation.

Plasma waves in a FET channel are similar to shallow water waves or to sound waves since they have linear dispersion law. In turn, shallow water behaviour is similar to the dynamics of a gas with pressure proportional to the square of the density [2]. Thus, the nonlinear hydrodynamic equations for the two-dimensional electron fluid are similar to (but not identical with) the equations for a real gas, such as air. However the linearized equations describing small amplitude plasma waves in a FET and sound waves in a gas are identical. Since the linearized equations determine the instability threshold for a steady flow (i.e. the wave generation threshold) , the instability conditions for a real gas and for a two dimensional electron fluid should be similar provided that the Reynolds numbers and the quality factors of resonance cavities are the same. We show that these dimensionless parameters for our "electronic flute" may be very close to those for a conventional flute, though the dimensional parameters (such as linear dimension, wave velocity, and oscillation frequency) differ by many orders of magnitude.

Thus, the complete similarity between the plasma waves in a FET and sound waves led us to believe in the possibility of realizing an electronic flute based on the excitation of plasma oscillation by direct current and operating in terahertz range of frequencies. The basic structure can be repeated many times and the device may be constructed as an array with dimensions equal to the quarter of the wavelength of the electromagnetic radiation with the same frequency.

9. CONCLUSIONS AND RECOMMENDATIONS

In this work we have studied theoretically various problems related to the hydrodynamic behaviour of the two dimensional electron fluid in the channel of a Field Effect Transistor. The most important physical feature of this system is the existence of plasma waves with a linear dispersion law. The FET channel together with the source and drain contacts forms a resonator for plasma oscillations with a quality factor about 10 for submicron devices. We have studied in detail the consequences of the direct current instability discovered in Ref. 1, and found additional types of instabilities, which should result in plasma wave generation in the terahertz frequency range. We have also found that the hydrodynamic (shallow-water-like) properties of the electron fluid may in some cases determine the shape of the FET steady state current-voltage characteristics.

It seems that a new field, which could be named "plasma wave electronics", may emerge as a result of these findings, and a new generation of terahertz devices, utilizing plasma oscillations in submicron FETs, such as oscillators, detectors, mixers, and frequency multipliers, could be implemented.

However a lot of research, both theoretical and experimental, should be done to achieve this goal. Experimentally, nanostructures specially designed for studying the plasma oscillations in gated two dimensional layers, should be fabricated, and their ability to generate and respond to terahertz radiation tested. Since the pioneering experimental work on plasma waves in FETs, performed almost 20 years ago [3, 4] with very poor quality (by modern standarts) Silicon devices, was succesfull, it would seem that such a task could be accomplished. Theoretically, the possibility of using a FET as a resonant and tunable detector of terahertz radiation, as well as a mixer, and frequency multiplier, by taking advantage of the nonlinear properties of the electron fluid, should be investigated. Computer simulation of the plasma wave dynamics, especially in the highly nonlinear regime, should also be done.

The results obtained in the course of this work were published in Refs. 8, 9, 11, 13, 14

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